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Considerations for Launching Amateur Rockets at X-Prize Cup 2006

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The X-Prize Cup event represents an opportunity for the general public to witness technology development in the areas of aerospace design, manufacture, and exhibition. Of particular interest is the exhibit of high performance amateur rockets. The goal of this exhibit is to allow the general public to safely view the launching of these high performance rockets. These amateur rockets vary in design with some vehicles at the 2006 event having very impressive size and capabilities, such as a height of 20 feet, weight of 500 lbs, speed of 1.2 Mach, and an altitude of 20,000 feet above ground level. The FAA worked with the rocket operators, Tripoli Rocketry Association and X-Prize Cup Foundation, to evaluate the safety of launching these amateur rockets. The FAA worked closely with the X-Prize Cup Foundation and Tripoli Rocketry Association to determine safe launching guidelines and requirements for amateur rockets launched at the X-Prize Cup event in Las Cruces, NM on October 20-21, 2006. This paper describes the analysis that supported the FAA decision to approve the X-Prize Foundation and Tripoli Rocketry Association Airshow waiver to launch amateur rockets at the X-Prize Cup event, and presents findings for evaluating high performance rockets, that are classified as "amateur rockets' by the FAA for regulatory purposes.

Nomenclature

u_1 = mean of data element 1 bivariate probability density function
u_2 = mean of data element 2 bivariate probability density function
ρ = correlation between data element 1 and data element 2
σ_1 = standard deviation of data element 1 bivariate probability density function
σ_2 = standard deviation of data element 2 bivariate probability density function
σ_{12} = covariance between element 1 and element 2
x_1 = data element 1 value
x_2 = data element 2 value
P = probability of bivariate ellipse
a2 = elliptical standard deviation term
rs = radius to point at desired theta at probability P
x = element 1 value along elipse
y = element 2 value along ellipse
θ = clock angle for probability ellipse
E_c = expected casualties
P_i = probability of impact
ρ_p = population density
Ca = casualty area

Phoenix XL Amateur Rocket Soars Skyward

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I. Introduction

Amateur rocketry has been an exceptionally safe hobby over the last 50 years; over 400 million amateur rocket flights have been conducted without a rocket induced fatality [2]. In an effort to maintain an excellent rocket safety record and reduce the hazards associated with rocketry, the Federal Aviation Administration (FAA) has worked in concert with amateur rocketry to create regulations, documented in the Code of Federal Regulations (CFR) Part 101 – Moored Balloons, Kites, Unmanned Rockets and Unmanned Free Balloons and CFR Part 401.5 – Definitions [5], that define amateur rockets and the associated requirements to ensure public safety. In addition to these regulations, the FAA has regulatory oversight of amateur rocket launches that affect airspace by implementing FAA order 7420.F – Procedures for Handling Airspace Matters, to insure air traffic safety in addition to public safety. These regulations provide the framework to ensure amateur rocketry is a safe and viable endeavor. The 2006 X-Prize Cup event provided members of the Tripoli Rocketry Association the opportunity to launch amateur rockets. This event was planned in an area where up to 20,000 spectators might be at the Las Cruces airport. The goal of the FAA was to protect air space and to promote safe spectator observation of the high powered amateur rocket launches. To ensure these goals the FAA performed extensive analysis in cooperation with the X-Prize Foundation and Tripoli Rocketry Association, to evaluate the safety of these planned amateur rocket launches and to help ensure an environment that would be safe for viewing by those attending the X-Prize Cup event.

Redstone Rocket Poised at Sunrise

II. Objective

The objective of the analysis was to develop safe guidelines and requirements for launching the Tripoli Rocketry Association rockets at the X-Prize Cup event. This included ensuring that the launch operations and safety analysis performed by Tripoli Rocketry Association and X-Prize Foundation provided spectators and participants with a safe event.

III. Authority

The FAA defines amateur rockets in CFR 14 Part 401.5. Individuals who launch high performance rockets are regulated by state and local government as well as the FAA. Tripoli Rocketry Association also influences these launches through its safety code.

Part 101 of CFR 14 applies to all unmanned rockets except model rockets that use not more than four ounces (113 g) of propellant and weigh not more than 16 ounces (453 g), including the propellant. Part 101 prohibits operating an unmanned rocket in a manner that creates a hazard to other persons or their property, or dropping an object from the rocket if such action creates a hazard to other persons or their property.

Part 101 also states that no person may operate an unmanned rocket in a manner that creates a collision hazard with other aircraft; in controlled airspace; within five miles of the boundary of any airport; at any altitude where clouds or obscuring phenomena of more than five-tenths coverage prevails; at any altitude where the horizontal visibility is less than five miles; into any cloud; within 1,500 feet of any person or property that is not associated with the operations; or between sunset and sunrise. Deviations from the requirements documented in Part 101 require waiver.

IV. Definitions

Amateur Rockets - In the regulations, launches of small-scale rockets of limited performance are termed "amateur rocket activities." Under CFR 14 Part 401.5, a launch constituting an amateur rocket activity is one that takes place from a private site and involves a rocket that meets all three of the following criteria:

- The rocket motor(s) has a total impulse of 200,000 pound-seconds or less;
- The rocket motor(s) has a total burning time or operating time of less than 15 seconds; and
- The rocket has a ballistic coefficient - i.e., gross weight in pounds divided by frontal area of rocket vehicle - less than 12 pounds per square inch.

E_c: Summation of probability of impact of rocket multiplied by population density of spectators multiplied by casualty area of rocket

NOTAM: Notice to airmen of controlled airspace to reflect airway changes and temporary flight restrictions.

Public Land: Land other than land owned by the applicant or land for which the applicant has attained written agreements with the land owner for exclusive use for the proposed launch.

- No public land over-flight or impact shall occur within an impact hazard area.
- No non-launch participants may be within the impact hazard area.

Wind Weighting: A technique used to predict launcher azimuth and elevation settings for unguided launch vehicles such that a rocket's flight through a forecasted wind field will produce the predicted nominal drag impact point for the final launch vehicle stage.

Recovery: Capture of all launch vehicle components that impact on public.

Maximum Nominal (no wind) Launch Angles: The nominal elevation and azimuth of the rocket launch rail system to ensure the E_c associated with a rocket launch is met.

Cross-range - The distance measured along a line whose direction is either 90 degrees clockwise (right cross-range) or 90 degrees counter-clockwise (left cross-range) to the projection of the launch vehicle velocity vector azimuth into a horizontal plane. This plane is tangent to the ellipsoidal earth model at the intersection point of a line and the earth's surface where the line is normal with the earth's surface and passes through the launch vehicle's current earth centered position.

Downrange - The distance measured along a line whose direction is parallel to the projection of the launch vehicle velocity vector azimuth into a horizontal plane. This plane is tangent to the ellipsoidal earth model at the intersection point of a line and the earth's surface where the line is normal with the earth's surface and passes through the launch vehicle's current earth centered position.

Drag Impact Point (DIP) - The drag impact point is defined at the intersection of a launch vehicle stage's or other impacting component's predicted ballistic trajectory with the earth's surface. This method of trajectory prediction includes the effects of atmospheric influences as a function of drag forces and Mach number.

Nominal Trajectory - The nominal trajectory is the trajectory that the vehicle will fly if all vehicle aerodynamic parameters are exactly as expected, if all vehicle internal and external systems perform exactly as planned, and if there are no external perturbing influences (e.g. winds) other than atmospheric drag and gravity.

Three-Sigma Vehicle Dispersion - Three-sigma dispersions define the expected up-range, downrange, and cross-range limits of normality for the launch vehicle.

Impact Dispersion - The statistical deviation of the actual impact point from the predicted nominal impact point. It is used to calculate the probability of impacting within a given distance of the nominal impact point.

Root Sum Square Dispersion - The square root of the sum of the squares of the individual impact dispersions of the vehicle.

Monte Carlo Dispersion - A dispersion approach where each dispersion parameter in the set of dispersions is randomly varied for each trajectory.

V. Method of Analysis for Waiver Evaluation

A. Target and Elevation Angle Determination

Often amateur rocket operators want to launch a rocket that does not meet the requirements of Part 101, for example burn time and total impulse of the rocket or location relative to an airport. When this happens the FAA requires the operator to apply for a waiver from the regulations. To ensure safe operations, regulations in concert with the guidance material developed by AST [6] for these activities were carefully considered in the evaluation of X-Prize Cup Airshow waiver to launch amateur rockets at the 2006 X-Prize Cup event. A key objective of the launch operations is to limit the E_c due to an off nominal rocket performance to zero. This objective is met using a statistical approach that limits the collective risk to the public to less than 30 casualties in a million launch attempts. This approach determines the appropriate target point for the launch of each rocket. The airspace closure requirement is determined by limiting the probability of impact of an aircraft not to exceed 1 impact per 10 million launches [7].

The expected casualties for a planned amateur rocket activity explicitly determine the target point at which to aim rockets. The FAA seeks an E_c of less than thirty out of one million rocket launches for amateur rocket launches. These requirements result in a required impact point which aids in determining a rocket launcher elevation angle. To perform these analyses one must perform statistical analysis of trajectory results obtained from the math modeling of the rockets to be launched and the appropriate characteristics of these launch vehicles. To accomplish this, the FAA AST used the capabilities of the TAOS (Trajectory Analysis and Optimization Software) [8] to perform a 6-Degree of Freedom (DoF) simulation of Tripoli Rocketry Association rockets that were scheduled to be launched at the X-Prize

Cup event. These simulations required obtaining rocket geometry, mass properties, propulsion, aerodynamics, and parachute performance data for each rocket Tripoli Rocketry Association planned to launch at the X-Prize Cup event. In addition a database that represented the Las Cruces wind environment during the planned launch date was required.

1. Rocket Trajectory Modeling

The FAA needed to identify each rocket's vehicle characteristics to generate a realistic mathematical simulation model which included:

1) Geometry: Rocket length, diameter and fin characteristics. We used these data to scale aerodynamic coefficients and build a mathematical model.

2) Mass Properties: Center of gravities for all three axes as a function of vehicle weight and principal axis inertias. We used these data to model the rocket's rotational characteristics.

3) Propulsion: Rocket sea level thrust versus time as well as the expected mass flow of the propellants versus time. (Note: Because these rocket burns for such a small duration of time and the altitude changes during the burn are minor, we needed only sea level thrust.)

4) Aerodynamics: Aerodynamic forces and moments in a prescribed reference system to appropriately model the effects of aerodynamics on the flight of the rocket. (Note: Because of the static stability of these rockets and the limited body attitude, we did not need flight angles stability derivatives for this assessment.)

5) Parachute Systems: Dimensions as well as drag area for each element of the recovery system.

6) Winds: Statistical mean and standard deviation wind representations of the Las Cruces winds for the month of October. Jimsphere measured winds at the X-Prize Cup event for the planned launch times.

7) Dispersions: Variations in the expected performance of each rocket, considering all of the vehicle and weather characteristics, launch erector elevations settings, and wind measurement uncertainties.

Table 1 summarizes some of the vehicle data obtained from Tripoli Rocketry Association and baselined for the safety evaluation.

Table 1. Summary of X-Prize Rockets Assessed by FAA-AST

Rocket	Weight	Length	Diameter	C_d (0)	Beta (ballistic coefficient)
	lb	ft	ft-2	Nd	lbs/in-2
Phoenix XL	500	18.44	1.38	0.3	7.8
Flag	183	20.00	1.38	0.3	2.9
Event Horizon	360	20.96	0.98	0.3	11.2
Dream Is Alive	90	10.83	0.64	0.4	5.0
Redstone	192	22.38	2.00	0.4	1.1

Rocket	Peak Thrust	Peak TOW	Burn Time
	lb	g's	Sec
Phoenix XL	3855	7.7	8
Flag	960	5.2	6
Event Horizon	1680	4.7	6
Dream Is Alive	1240	13.7	4.2
Redstone	2200	11.5	7.75

Rocket	Max Impulse	Impulse Per Unit Weight	Motor
	lbs-sec	sec	nd
Phoenix XL	30840	61.7	Q
Flag	5760	31.5	O
Event Horizon	10080	28.0	3xN
Dream Is Alive	5208	57.7	N
Redstone	17050	88.8	P

Table 2 summarizes the rocket dispersion parameters used to generate the trajectory dispersions used in the safety evaluation.

Table 2. Rocket Dispersion Parameters Used in Tripoli Rocket Safety Evaluation

Dispersion Category	Mean		1 Sigma Baseline Dispersions [4]
Launcher			
Elevation (degrees)	85.0		0.083
Azimuth (degrees)	0.0		0.333
Aerodynamics			
Axial Force Coefficient (factor)	1.0		0.067
Pitch Moment Coefficient (Δ)	0.0		0.01
Yaw Moment Coefficient (Δ)	0.0		0.01
Rocket Physical Characteristics			
CG offset, y-direction (ft.)	0.0		0.0028
CG offset, z-direction (ft.)	0.0		0.0028
Nozzle offset, y-direction (ft.)	0.0		0.014
Nozzle offset, z-direction (ft.)	0.0		0.014
CG offset, x-direction (ft.)	0.0		0.056
Thrust angle offset, Pitch (deg)	0.0		0.033
Thrust vector Roll angle (deg)	0.0		180
ΔThrust (factor)	1.0		0.1
Center of Pressure offset (ft)	0		0
Moment of Inertia (factor)	1		0
Weight (factor)	1		0

The FAA used a linear regression evaluation of a typical rocket [1] to determine which dispersions sources maximized the dispersion in the trajectory parameters. Figures 1 and 2 summarize data obtained from this analysis and show that the key dispersion parameter in determining trajectory downrange and cross-range dispersions is thrust vector misalignment.

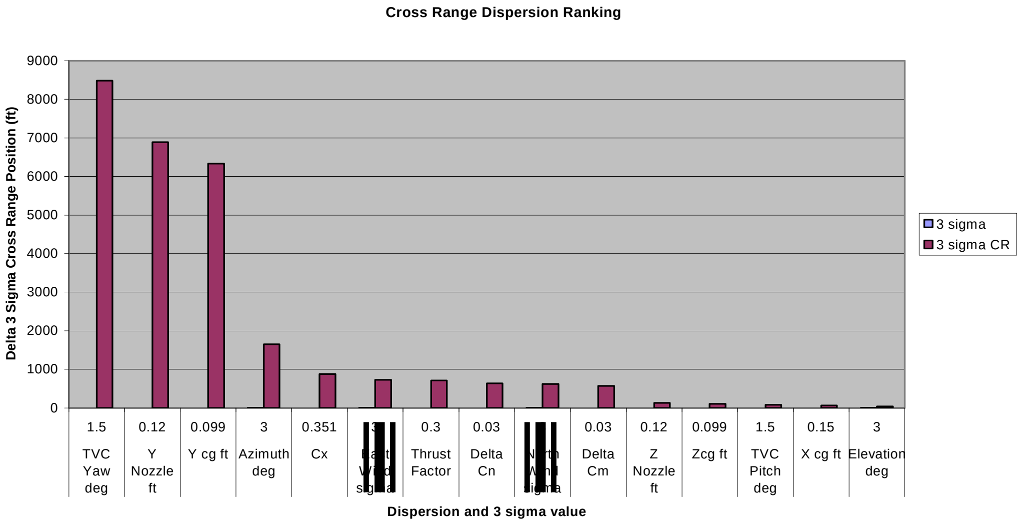


Figure 1. Linear Regression Cross-range impact position versus 3 sigma parameter dispersion (dispersed trajectories).

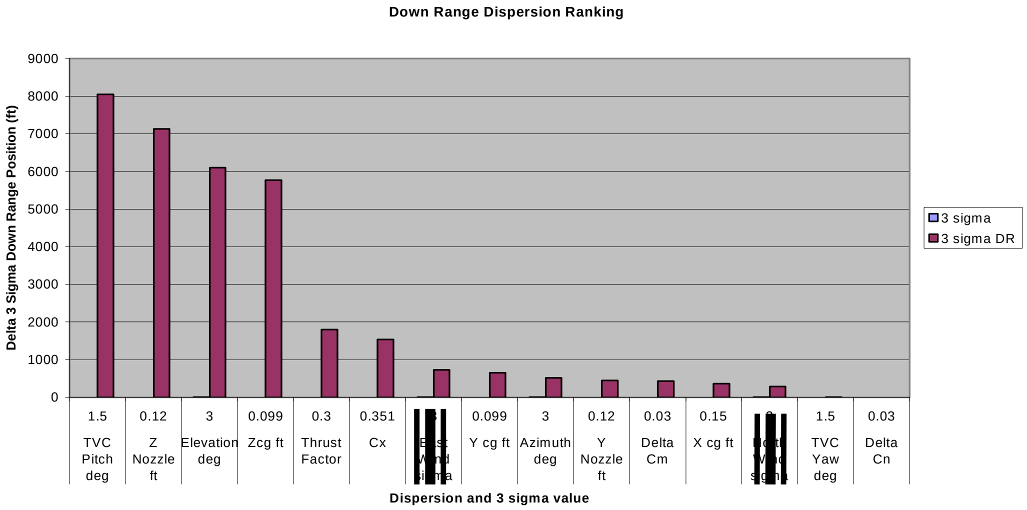


Figure 2. Linear Regression Downrange impact position versus 3 sigma parameter dispersion (dispersed trajectories)

2. *Crowd Modeling*

We modeled crowd characteristics to calculate the E_c and P_i due to a rocket impact in the spectator area or the probability of impact (P_i) of the rocket in the spectator area. We identified the following information as required data:

1) Spectator areas: Include the boundaries where all non-participants could be. We expected all spectators to be remain within a rectangular area of 2,150 feet by 600 feet boundary approximately 2,000 feet directly behind the launcher.

2) Launch Area: Area where the rockets would be launched. The rocket launch location was a minimum of 2,000 feet directly in front of the spectator area.

3) Population area: Expected population in the X-Prize spectator area. X-Prize Foundation estimated a maximum of 20,000 spectators at any one time during the X-Prize event.

4) Population density: The maximum population of the expected number of spectators divided by the expected spectator area.

3. *Rocket Casualty Area Modeling*

The FAA defined rocket casualty area by the rocket characteristics as it impacts the ground. We generated a conservative value for the rocket area of 550 square feet based upon the characteristics of the largest rocket to be launched at the X-Prize Cup event. The casualty area included accommodations for the expected flight path of the rockets during impact as well as potential bounce and splatter of the fragmented rocket pieces.

4. *Statistical Modeling of Probability of Impact*

The key to determining the P_i of the amateur rockets into the spectator view area was evaluating the nominal and dispersed trajectories. Once we modeled the nominal and dispersed properties, we evaluated the properties in a statistical manner using a bivariate normal distribution to calculate P_i as shown below in equations 1 through 3. For these analyses we modeled 1,000 trajectories using the predefined dispersions and we ran each dispersion variable using a Monte Carlos technique.

$$P(x_1, x_2) = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}} \exp\left[-\frac{z}{2(1-\rho^2)}\right], \quad (1)$$

$$z \equiv \frac{(x_1-\mu_1)^2}{\sigma_1^2} - \frac{2\rho(x_1-\mu_1)(x_2-\mu_2)}{\sigma_1\sigma_2} + \frac{(x_2-\mu_2)^2}{\sigma_2^2}, \quad (2)$$

$$\rho \equiv \operatorname{cor}(x_1, x_2) = \frac{\sigma_{12}}{\sigma_1\sigma_2} \quad (3)$$

To employ these equations, we tested the trajectory data, downrange and cross-range variations to see if they qualitatively met a normal distribution (Note: We observed that 1,000 data sets produced an acceptable output.). Figures 3 and 4 show a histogram of the downrange and cross-range variations obtained from the dispersion analysis. These data support our using a bivariate normal distribution to calculate probability of impact. Once we obtained the statistical inputs, we obtained the P_i in the spectator area by numerically integrating the probability density function with a fourth order Runga Kutta integrator.

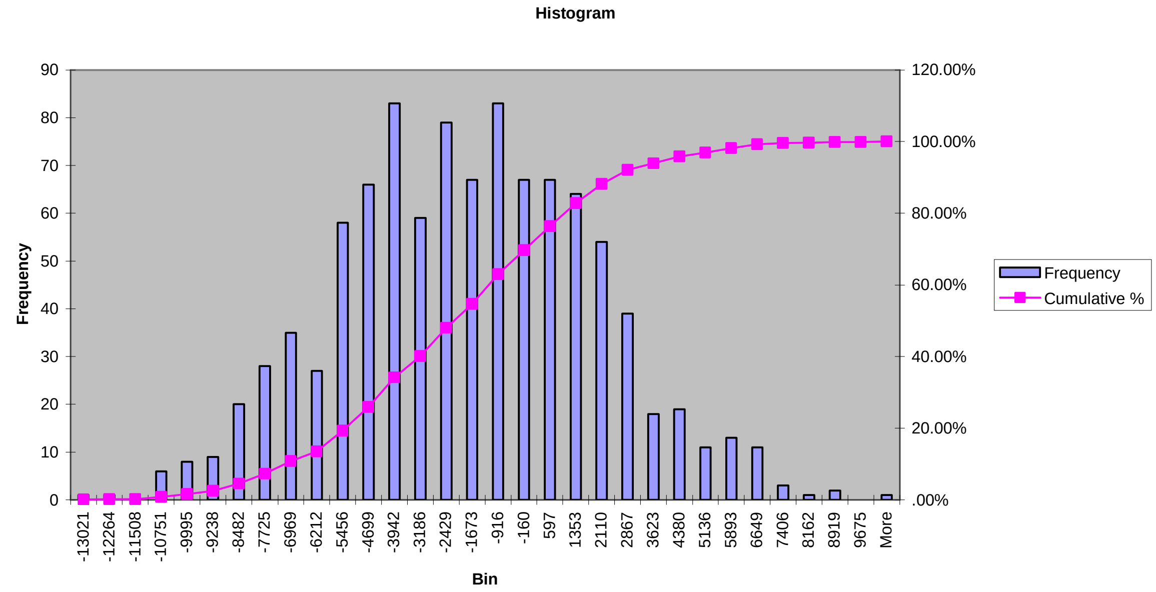


Figure 3. Histogram of Crossrange Impact Position Dispersed Trajectories

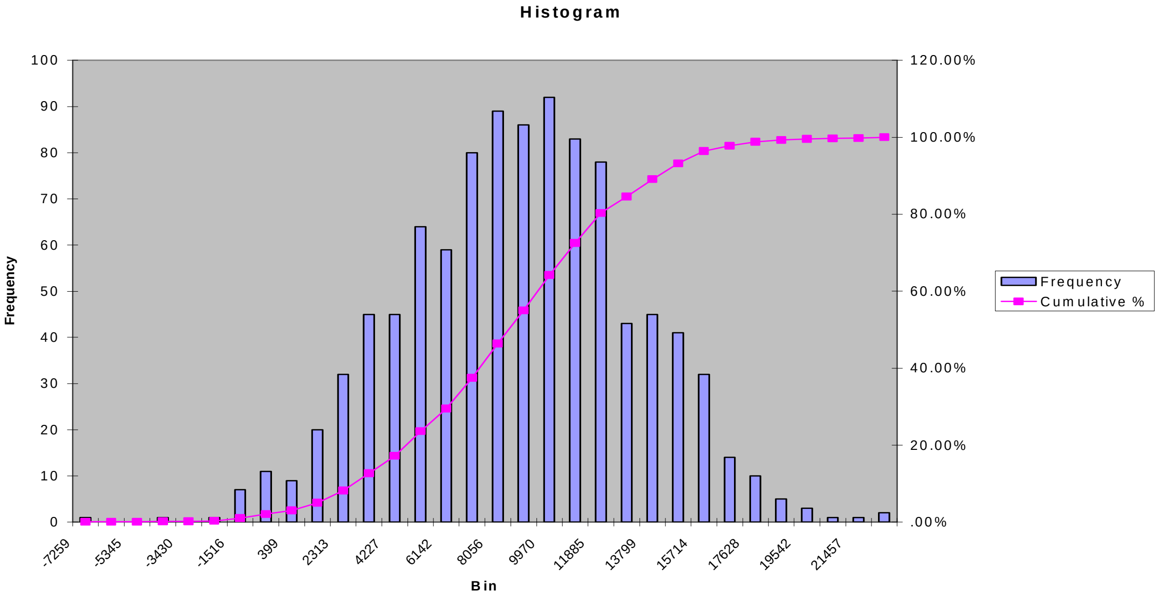


Figure 4. Histogram Downrange Impact Position Dispersed Trajectories

The FAA also used statistical characteristics of the trajectory dispersions to generate a bivariate probability ellipse. The bivariate ellipse describes the regions where all of the dispersed trajectories are expected to impact given a specified probability for the ellipse (P). Equations 4 through 7 describe the equations used to construct the P probability bivariate ellipse. Figure 5 shows representative trajectory data for a Tripoli Rocketry Association rocket and shows the nominal, dispersed, and normal bivariate ellipse for a probability of 99.73%.

$$a2 = 1/(1-\rho^2)*((x/\sigma_1)^2-(2*\rho*x*y)/(\sigma_1*\sigma_2)+(y/\sigma_2)^2) \qquad (4)$$

$$rs = ((-2*\log(1-P))/(a2))^{.5} \qquad (5)$$

$$x = \mu_1+rs*\cos(\theta) \qquad (6)$$

$$y = \mu_2+rs*\sin(\theta) \qquad (7)$$

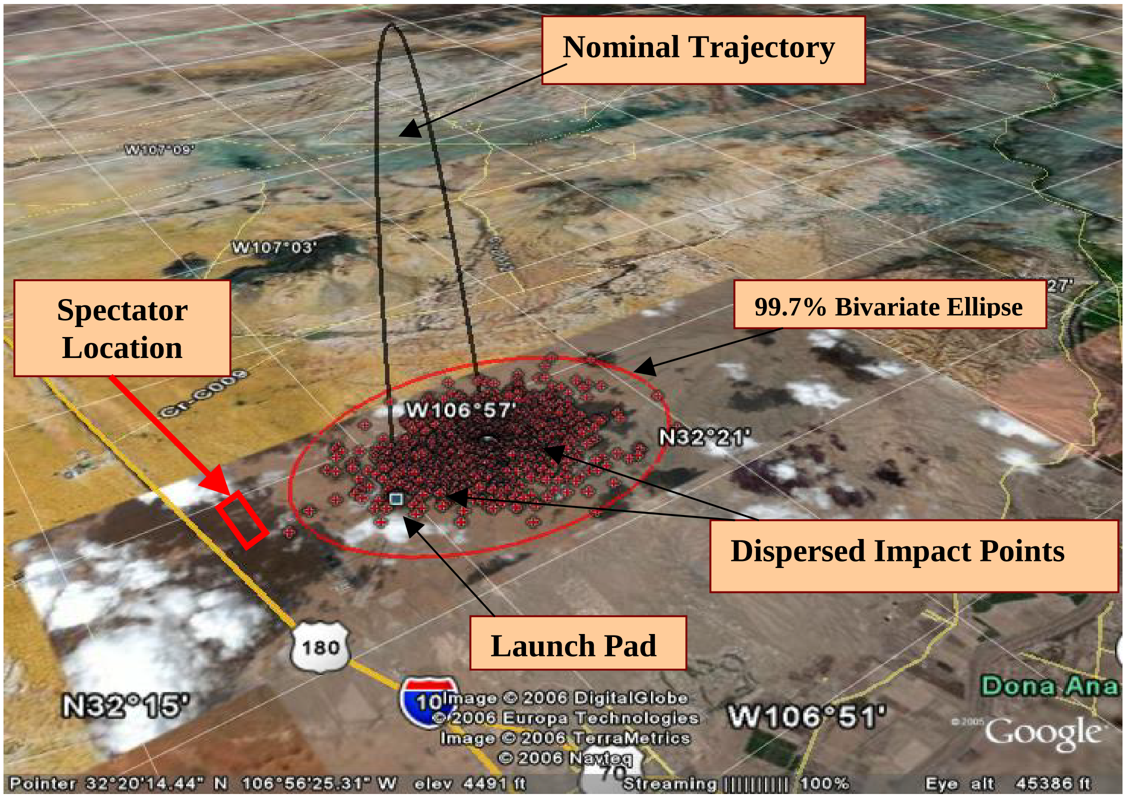


Figure 5. Las Cruces Airport with Nominal, 1000 Dispersed Impact Trajectories, and Launch Pad .

5. E_c *vs Probability of Impact Modeling*

The FAA investigated two methods of protecting spectators by evaluating the amateur rocket simulated trajectory data. The first method was to compute the E_c as shown in equation 8. The second used the P_i within the spectator area. Our results [1] showed that the probability of impact resulted in a more conservative assessment of risk to the spectators, by requiring a target further downrange of the rocket launch point, and thus we assessed P_i into the spectator area for the final safety determination.

$$E_c = \iint P_i \times \rho_p \times Ca \, dxdy \qquad (8)$$

6. Target and Elevation Angle Determination

With a method of computing the P_i, the FAA could evaluate the effect of placement of the rocket impact point on probability of impact into the crowd. The rocket impact point was varied by adjusting the launch elevation of the rocket until the probability of impact into the spectator area of less than one in a million was achieved.

1) Elevation Angle: Because amateur rockets are unguided, the impact point is achieved by adjusting the rocket launcher elevation angle. Knowledge of the required impact target resulted in a required rocket launcher elevation setting. At the X-Prize Cup event, we required launcher elevations be set to achieve the required P_i.

7. *Probability of Failure*

A successful parachute deployment mitigated the risk associated with the launch of the amateur rockets, the FAA considered the probability of the parachute failing to open in our target determination. The Tripoli Rocketry Association characterized their recovery system success as 95%, thus the FAA chose a 5% failure in its evaluation of a required impact target.

8. Wind Weighting

The FAA used wind weighting to achieve the desired vehicle impact target by applying the measured wind the rocket would travel through. The wind weighting evaluation had to take into consideration that the wind could change between the time of the wind measurement of the wind tower and the Jimsphere weather balloon at the launch location and the actual time of the rocket launch. Historical wind data indicated that a half hour variation in wind could be considered as 25 percent of the wind 3-sigma steady state variation for a given month. Thus the FAA allowed for 25 percent wind variation in addition to 3-sigma dispersions when computing required vehicle impact targets. Figure 6 illustrates the effect of wind weighting on a 3-sigma wind trajectory showing the nominal trajectory, the 3-sigma tail wind trajectory without wind weighting, and the wind weighted trajectory. As shown by the data presented in Figure 6 the wind weighted trajectory looks very similar to the nominal trajectory (the elevation may be quite different).

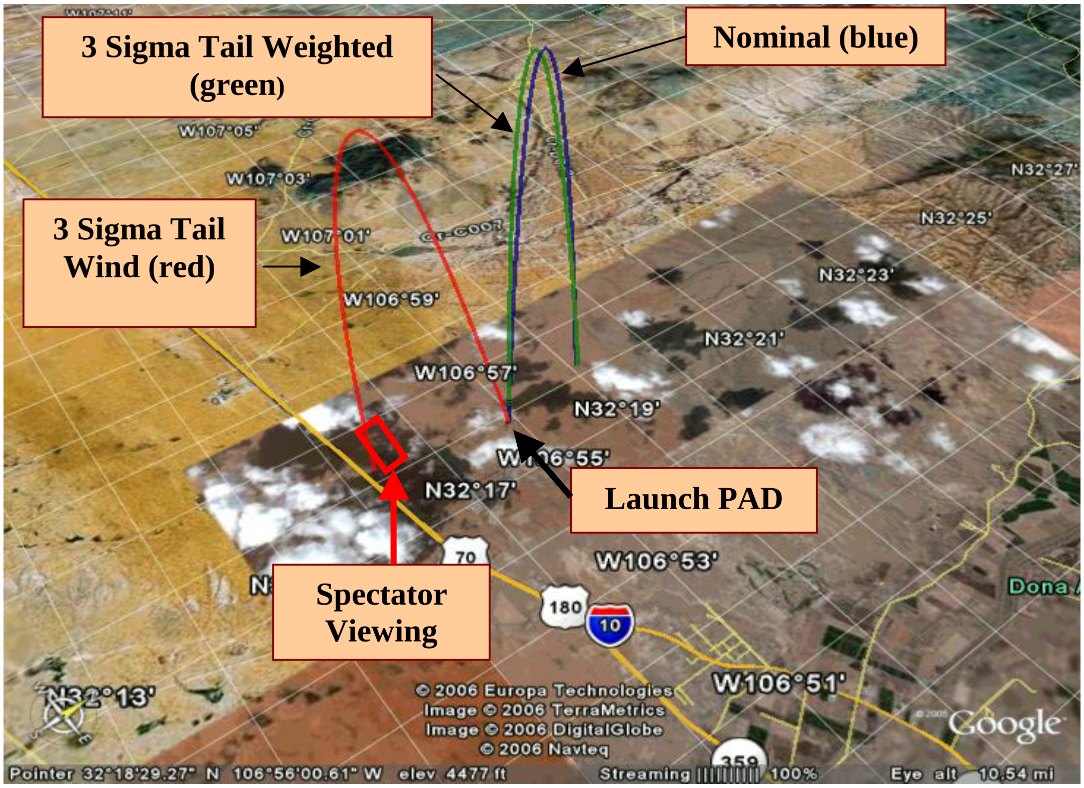


Figure 6. Wind weighting example for a 3-Sigma Las Cruces tail wind.

9. *Airspace Requirements*

The highest amateur rocket altitude planned at X-Prize Cup was 21,000 feet AGL. Therefore it was necessary to protect aircraft from these high flying amateur rockets. X-Prize foundation proposed a 5-nautical mile radius about the rocket launcher area. The FAA performed a P_i analysis [1] to determine the area required to protect a probability of impact to an aircraft of 1 in 10 million and found that the X-Prize Foundation boundary was conservative. The FAA evaluation considered the swept out area of a Boeing 747 flying along the area space perimeter using the statistical dispersion data of the rockets to obtain a location of the aircraft that maintained the required level of probability of impact. The radius of this area was less than the X-Prize Foundation proposed airspace restriction. The X-Prize Foundation airspace restriction was used in generating a Notice to Airman. Figure 7 shows the resulting airspace requirement using the conservative Phoenix XL rocket was much less than a 5-nautical mile radius.

10. *Airshow Waiver Terms and Conditions*

The FAA issued a list of terms and conditions [5] that applied to the airspace waiver [6]. The terms and conditions expressed specifics about the launch operations and launcher setting for the Tripoli Rocketry Association amateur rocket launches and became part of the waiver requirements.

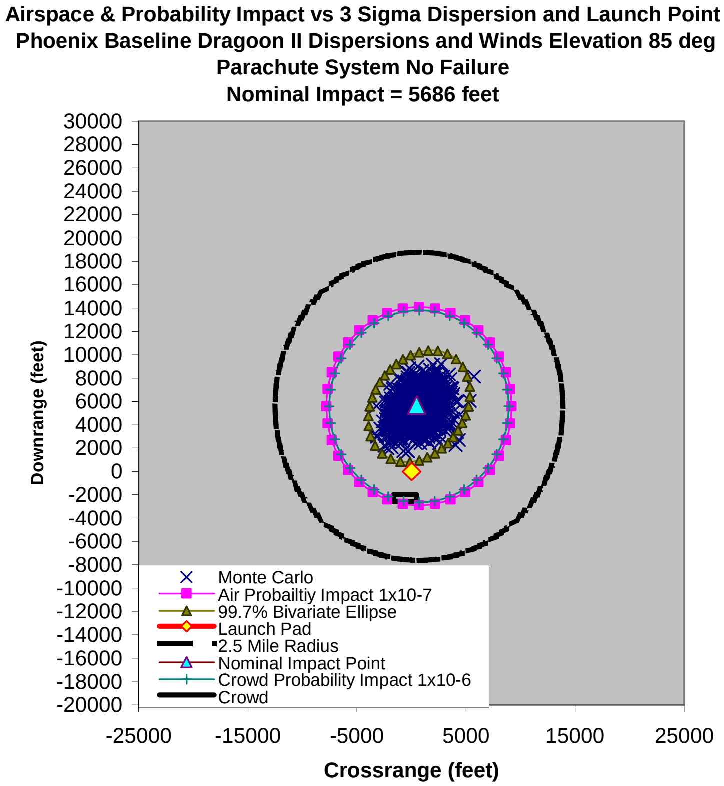


Figure 7. Example Airspace and Probability of Impact for a launch elevation of 85 degrees

B. Compliance Monitoring

It is the responsibility of the rocket launch operator to comply with the terms and conditions of the approved waiver. The FAA attended the X-Prize Cup event amateur rocket launches to ensure that rocket launchers complied with the terms of the terms and conditions of the approved waiver [7].

C. Simulation Validation

A key element of compliance monitoring is the validation of the simulation tool the Tripoli Rocketry Association would use to assess the performance of their rockets on the day of launch. Tripoli uses SPLASH, a 6-DoF simulation tool that simulates the rocket flight. The FAA used TAOS to validate the SPLASH simulation tool for use on the day of launch to determine elevation angles required to hit the required vehicle impact target. The FAA compared simulation data from each software application using proposed launch vehicle data. This analysis demonstrated good agreement between the two simulations tools and supported Tripoli Rocketry Association and X-Prize Foundation using the SPLASH simulation tool on the day of launch. Table 3 and Figures 8 and 9 summarize the simulation validation results.

Table 3. Simulation Comparison of Nominal Trajectory Based on TAOS & SPLASH Results: Phoenix XL

Event	Time (sec)	Altitude AGL (ft)	Relative Velocity (ft/sec)	Downrange (ft)	Cross range (ft)
Booster Ignition	0	0	0	0	0
SPLASH Booster Burnout	7.84	6256	1243	791	-3.6
TAOS Booster Burnout	7.95	6005	1244	742	-3.6
SPLASH Apogee	35.69	20281	95	4361	-60.43
TAOS Apogee	36.12	20754	109	4240	-55.1
SPLASH Ground Impact	71.3	0	1135	8310	-96
TAOS Ground Impact	75.2	0	848	7794	-86.5

SPLASH vs TAOS: PHOENIX XL
Vehicle Simulation
85 Degree Elevation Launch Angle
Zero Wind

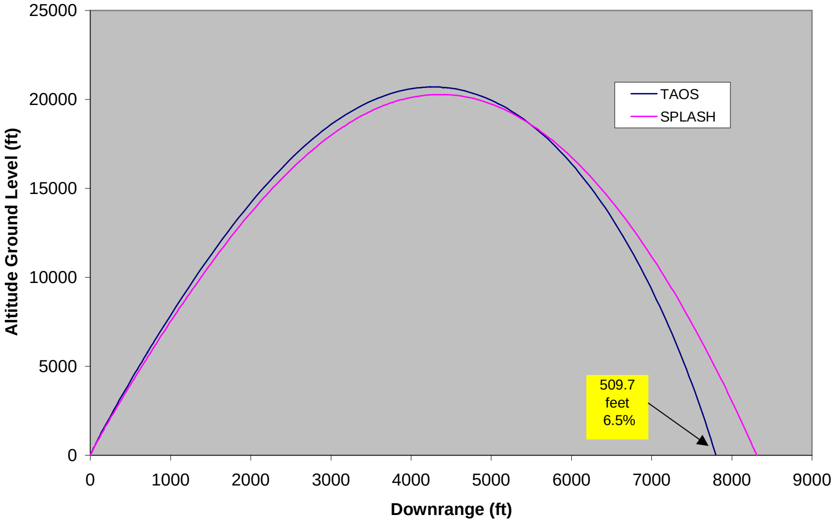


Figure 8. Simulation Validation Downrange Comparisons: Phoenix XL

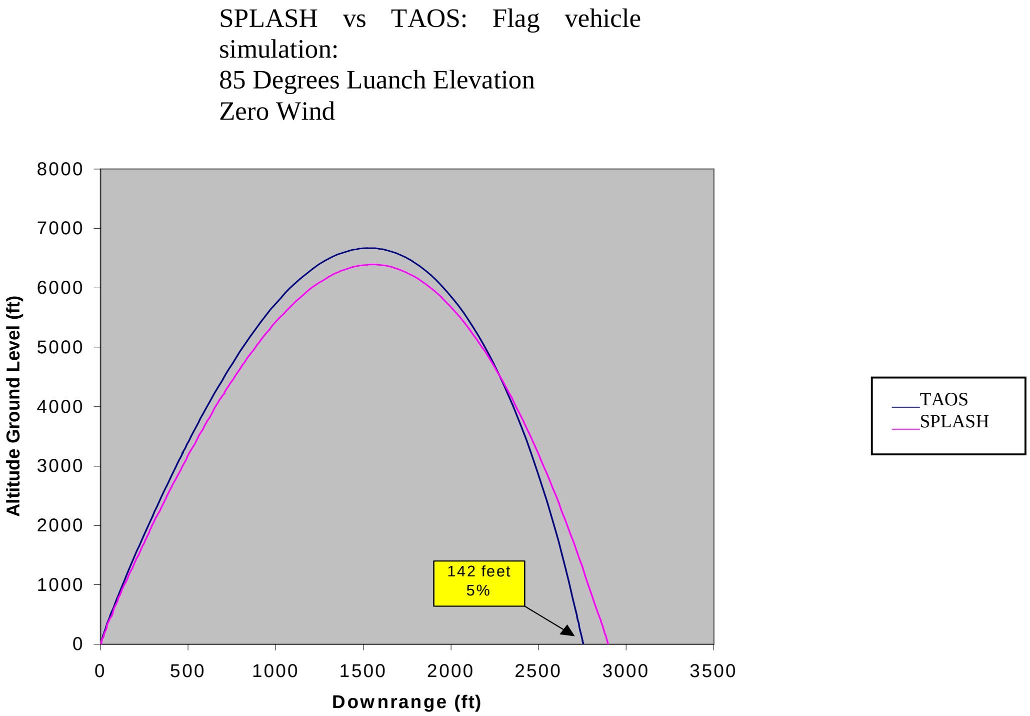


Figure 9. Simulation Validations Comparisons for Cross-range: Flag

D. Rocket Inspection

The FAA inspected each amateur rocket and launching rail to ensure compliance with the Airshow waiver. The FAA examined each amateur rocket to determine if the vehicle represented what was modeled and simulated. The FAA also inspected the rocket launch rails to ensure they could adequately launch at the required elevation angle.

E. Wind Measurements

A key requirement of wind weighting is to measure the wind environment prior to setting the desired launch rail elevation. Wind data consisted of tower anemometer data obtained from a multi segmented 200-foot tower and Jimspheres released near the launch site one-hour prior to the launch of each amateur rocket. Tripoli Rocketry Association input these data input into the SPLASH trajectory simulation tool to wind weight the rocket to an elevation setting that would achieve the desired impact target.

F. Elevation and Azimuth Setting Angles

Tripoli Rocketry Association obtained the launch elevation angle setting by mechanically adjusting the launch rail. Tripoli Rocketry Association used an inclinometer to set the rail elevation angle to the nearest tenth of a degree. They set the launch rail azimuth to zero degrees, due North, to point the vehicle toward the Bureau of Land Management property and away from the spectators.

VI. Results

A. Targets and Elevation Angle for Each Rocket

The target for each of the amateur rockets is shown in table 4. We generated a maximum allowable elevation setting for each target. Of the 8 rockets planned to launch, only 5 had enough vehicle information prior to the X-Prize Cup event to completely evaluate. As shown in reference [4], in agreement with Tripoli Rocketry Association, the FAA concluded that a baseline elevation angle set at 84.5 degrees would achieve the minimum required target aim point for each amateur rocket launched. The actual elevation obtained on the day of launch as a result of wind weighting to a ballistic impact point, which was greater than the minimum target to protect for $P_{i,}$ is also shown.

Table 4. Summary of Amateur Rocket Target Aim Point, Maximum Allowable Elevation, Wind Weighted Elevation on Day of Launch, and Rocket Apogee

Vehicle	Minimum Target Aim Point	Elevation Angle	Day of Launch Elevation	Apogee (AGL)	Crowd Offet
	ft	deg	deg	Ft	ft
Phoenix XL	6000	84.5	84.0	21000	2000
Flag	2200	84.5	84.0	7000	2000
Event Horizon	3800	84.5	82.5	9700	2000
Dream Is Alive	3600	84.5	84.0	14100	2000
Redstone	2200	82.7	No Launch	9444	2000

B. Post-flight Impact Location

Tripoli Rocketry Association determined the actual rocket impact points by using a hand held global positioning system (GPS). Figure 10 depicts the impact points for all of the amateur rockets launched by the Tripoli Rocketry Association at the X-Prize Cup event. Note that the one anomaly for the After Shock rocket was a result of a main parachute that deployed at apogee and the prevailing crosswinds that carried the vehicle crossrange.

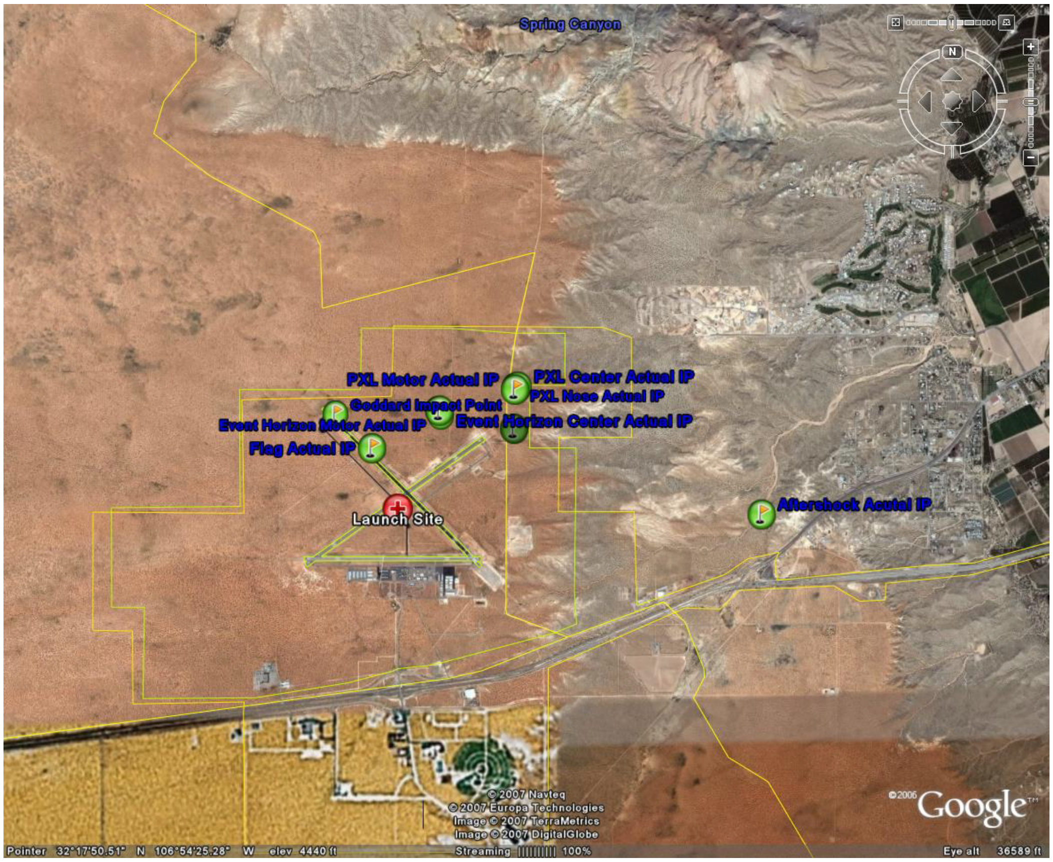


Figure 10. GPS Recorded Actual Impact Points for Launched Amateur Rockets

C. Post flight vs Preflight Prediction Comparisons

The FAA reconstructed the trajectories of the launched amateur rockets by using the known day of launch elevation angle and the launch minus one hour Jimsphere wind. Figures 11 through 14 show the preflight predictions and the post-flight results for each of the Tripoli rockets launched. The graphics show the required target, the predicted target given the L-30 minute Jimsphere wind, the Monte Carlos dispersed trajectories about the L-30 prediction, the 3-sigma bivariate ellipse at a probability of 99.73, and the actual recovered impact point of the rocket. The data shows that all the amateur rockets were near or within the boundary of the 3-sigma predictions. Finding two of the four launched rockets just outside the 3-sigma Monte Carlos predictions is an indicator that the rocket dispersions may have been larger than what was accounted for in the Monte Carlos dispersion analysis.

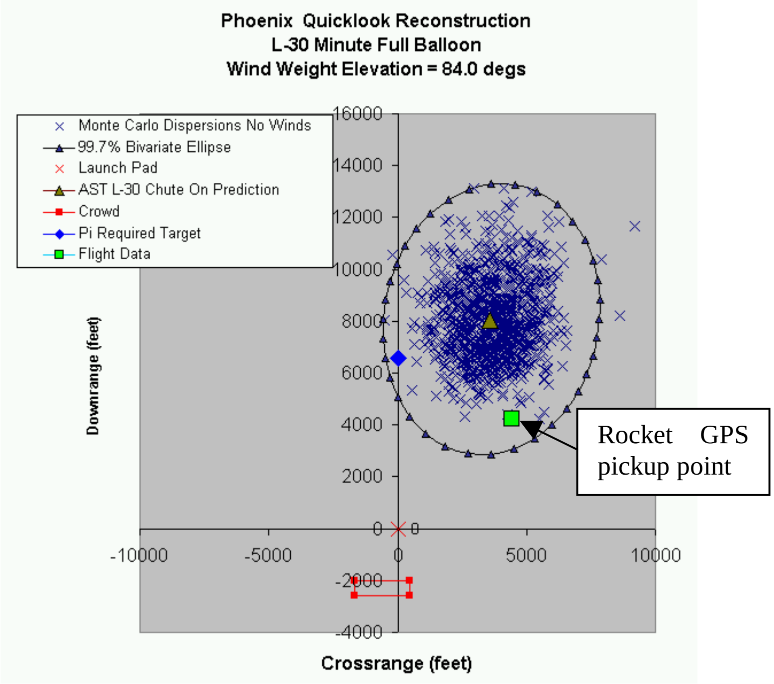


Figure 11. Phoenix XL Rocket Reconstruction

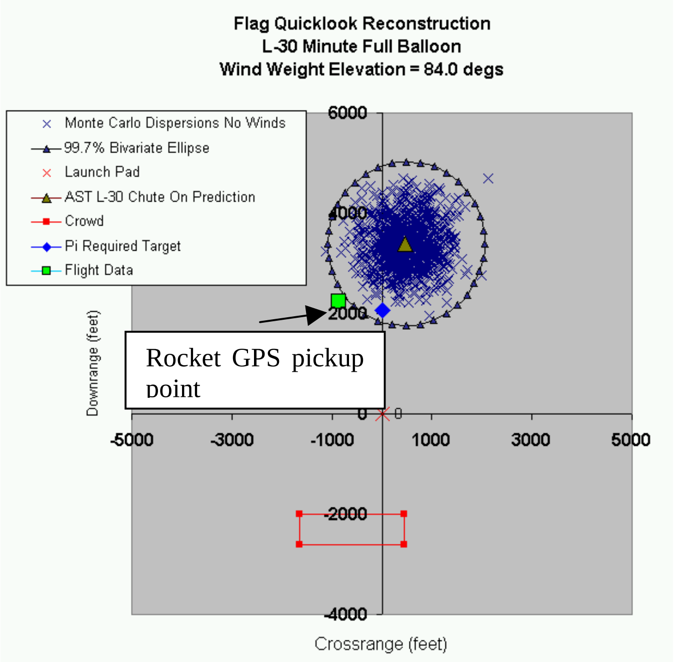
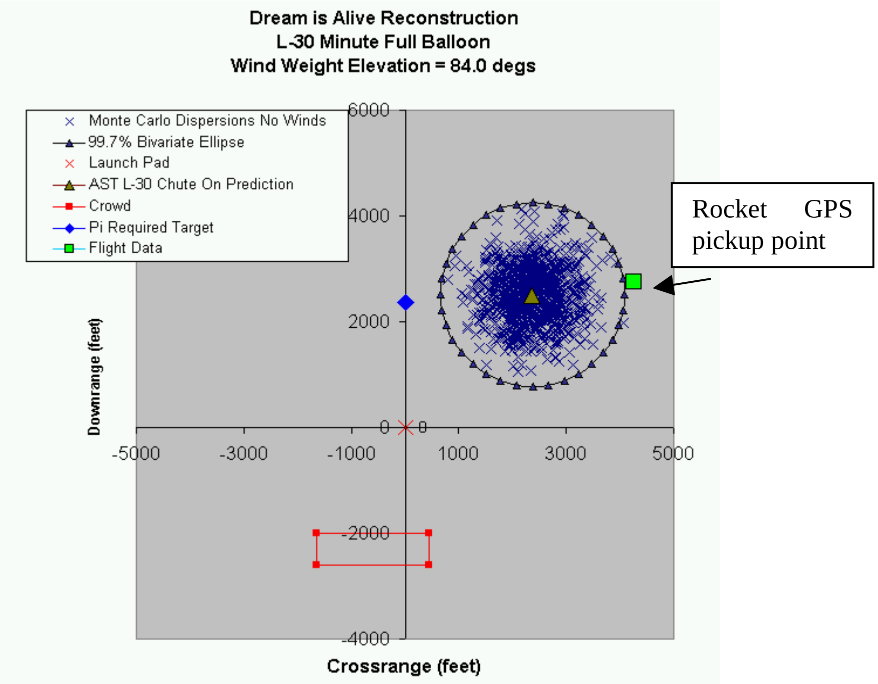
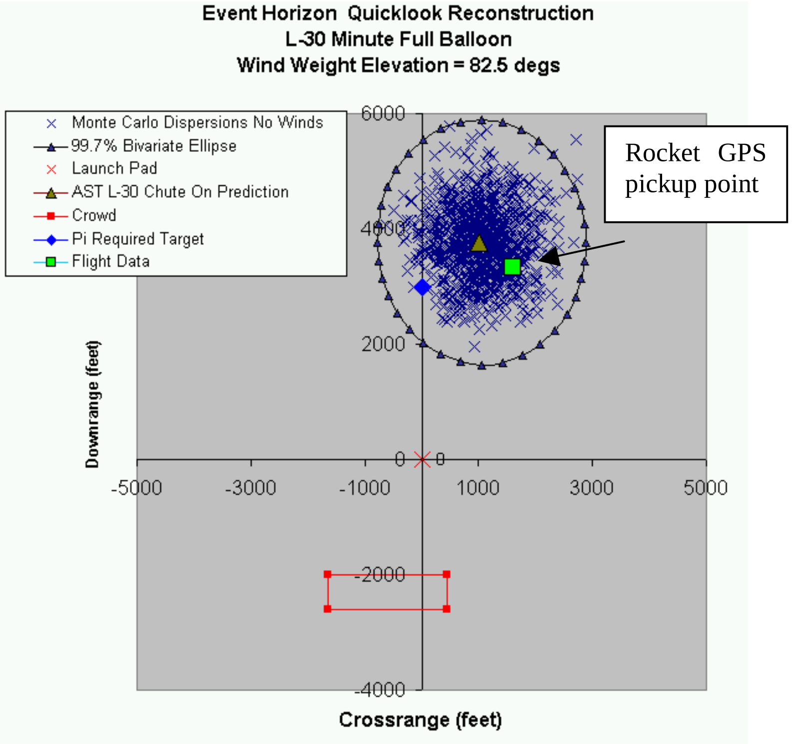


Figure 12. Flag Rocket Reconstruction



Rocket GPS pickup point

Figure 13. **Dream is Alive Rocket Reconstruction**



Rocket GPS pickup point

Figure 14. **Event Horizon Rocket Reconstruction**

D. Postflight Wind Analysis

Winds were a key input in the wind weighting of the amateur rocket trajectories to achieve the required target impact point. Figures 15 and 16 plot the crosswind and headwind components of the L-30 Jimsphere wind data used to support the launch of the Dream is Alive amateur rocket compared to the 3-sigma and mean statistical winds for Las Cruces for the month of October. This amateur rocket launched early in the morning on the second day of the X-Prize Cup event. The wind characteristics show relatively strong head winds and crosswinds. The head wind component resulted in a more depressed launch wind weight elevation setting relative to the baseline wind weight elevation setting of 84.5 degrees. After wind weighting for the Jimsphere measured wind, the rail elevation angle was set to 84.0 degrees for the Dream is Alive amateur rocket.

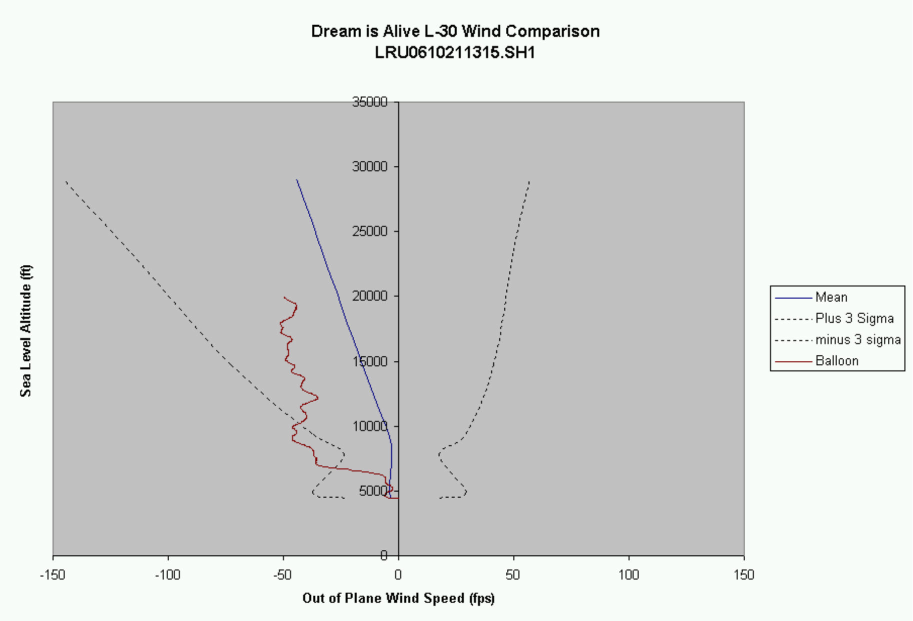


Figure 15. L-30 Minute Out of Plane Jimsphere Wind Data Used to Wind Weight Dream is Alive Rocket

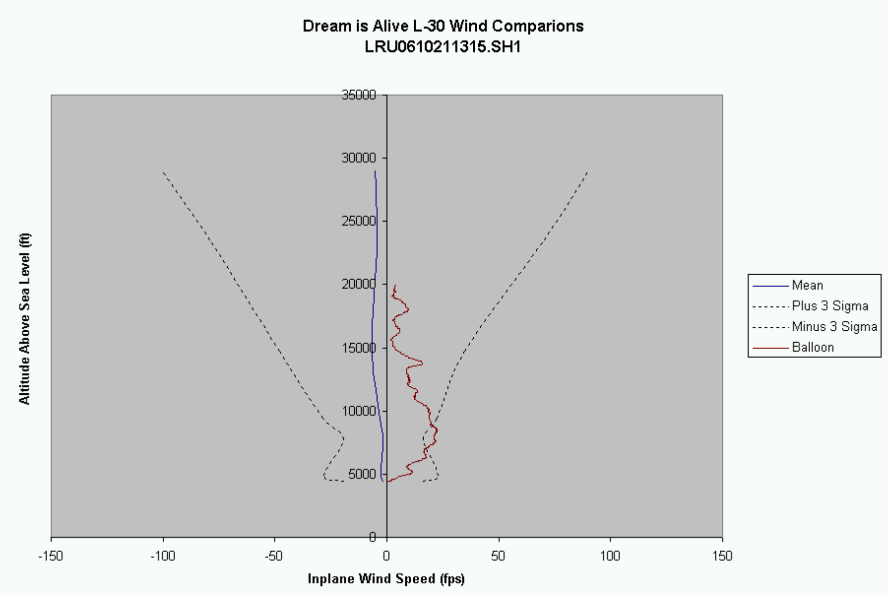


Figure 16. L-30 Minute in Plane Jimsphere Wind Data Used to Wind Weight Dream is Alive Rocket

VII. Conclusion

Post-flight analysis indicates that the amateur rocket trajectories did not result in any unexpected increase in risk to the spectators at the X-Prize Cup event. However we learned some valuable lessons and include the following:

1) Launching organizations simulation tool should be able to model multiple parachute recovery systems (i.e. drogue chute and main chute).
2) Launching organizations simulation tools should be able to input a complete wind profile.
3) Launching organizations simulation tools should be able to iterate internally on a wind weighting solution given a required target.
4) Amateur rocket parachute failure probability should be further refined.
5) Dispersions parameters should be re-evaluated.

Acronyms

CFR – Code of Federal Regulation
TAOS – Trajectory Analysis and Optimization Software
FAA – Federal Aviation Administration
AST – Commercial Space Transportation Office
ATO – Air Traffic Organization
AGL – Above Ground Level
DoF – Degrees of Freedom
GPS – Global Positioning System

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References

[1] FAA Memorandum , “X-Prize Aurora Baseline Assessment”, 22 September, 2006
[2] Final Report of the Special Committee on Range Operation and Procedure to the National Association of Rocketry, “Launching Safely in the 21st Century,” October 29, 2005
[3] Title 14 Code of Federal Regulations Part 100 through Part 1199, Aeronautics and Space, 1 January, 2006
[4] FAA Tripoli Rocket Safety Approval: X-Prize Cup Las Cruces, New Mexico, 20 October, 2006
[5] FAA X-Prize Cup Special Provisions for Tripoli Launches, October 20, 2006
[6] FAA Current Practice, June 1, 2001.
[7] X-Prize Cup Certificate of Waiver or Authorization, October 17, 2006
[8] Trajectory Analysis and Optimization Software (TAOS), ”Applied Aerospace Engineering and Advanced Concepts Department Sandia Laboratories”, March 2006